2.2 Charts, Graphs and Diagrams

Control Charts

Statistical process control was developed as a feedback system that aids in preventing defects rather than allowing defects to occur. One element of a process control system is control charts. Dr. Walter Shewhart defined the concept of common and special cause variation during the 1920s at Bell Laboratories. He developed a tool that he called the control chart, which could graphically depict variation. This control chart, could also distinguish the two types of variation from each other, thus allowing for the elimination of special causes and the reduction of common cause variation.

There are several types of variables data and attributes data control charts. This section will discuss the different types of control charts, the applications of each control chart, and the interpretation of the data.

Types of Control Charts

Variables data are quantitative data that can be measured. Some examples are the diameter of a bearing or the thickness of a newly minted coin. Variables data are usually represented as X-bar and R-charts and X-bar and s-charts.

Attributes data are qualitative data that can be counted. Some examples are a count of scratches per item or a count of acceptability for a go/no-go gauge. Attributes data are usually represented as nonconforming units and are analyzed by using p, np, c, or u control charts.

First, determine what variable you will measure. Then gather data and chart the data accordingly (Figure 2.2).

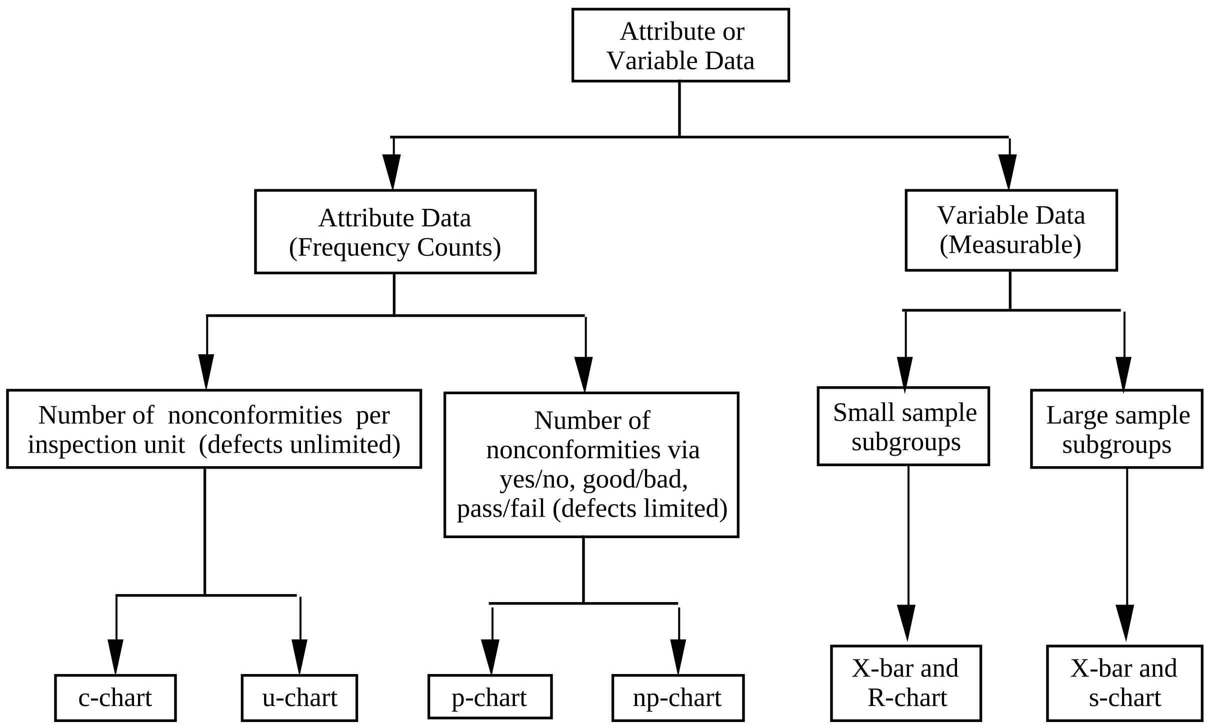

Figure 2.2
Sample Control Chart

X-bar and R-charts

The principal types of control charts used to analyze variables data are X-bar and R-charts. X-bar and R-charts are used in conjunction with each other. The measurements describe a process characteristic and are reported in small subgroups of constant sizes (usually two to five measurements per subgroup). Construction and use of these types of charts typically involve the following steps:

- Select the size, frequency, and number of subgroups.
- Assemble the data for the periods of interest.
- Calculate the average (X-bar) and the range R of each subgroup.
- Plot the averages and ranges on the control charts.
- Calculate the central line control limits; plot them on the control chart.
- Study the charts for stability and/or trends.

X-bar and s-charts

X-bar and s-charts (sample standard deviation) are also used in conjunction with each other and are measured from process characteristics. The sample standard deviation is a more efficient indicator of process variability, especially with larger sample sizes. However, it is more difficult to calculate and is less sensitive in detecting special causes of variation that cause only a single value in a subgroup to be unusual. Construction and use of these types of charts typically involve the following steps:

- Select the size, frequency, and number of subgroups.
- Assemble the data for the periods of interest.
- Calculate s, s-bar (average), and the control limits for both the X-bar and s chart, and the X-double bar chart.
- Plot the data on the control charts.
- Calculate the central line control limits; plot them on the control chart.
- Study the charts for stability and/or trends.

X-charts

Unlike X-bar and R-charts, which collect and evaluate subgroups of data, X-charts (sometimes referred to as individuals charts) involve the analysis of individual measured quantities for indications of process control or unusual variation. The standard deviation for X-charts is calculated using a moving range.

The following process should be used in developing and analyzing X-charts:

- Assemble data for the periods of interest.
- Calculate the average of the individual values.
- Calculate the individual moving ranges (all ranges will be positive numbers).
- Average the ranges.
- Calculate the standard deviation and subsequent control limits for the individual values.
- Plot the average and limit lines for the individual values and analyze for trends.

C-chart

The c-chart is the principal type of control chart used to analyze attributes data. C-charts (sometimes referred to as "count" charts) are used in dealing with counts of a given event over consecutive periods of time. The following process should be used in developing and analyzing c-charts:

- Assemble data for the periods of interest.
- Calculate the data central line.
- Calculate the upper and lower control limits.
- Plot central line, and control limits.
- Study the charts for stability and/or trends.

U-chart

U-charts (sometimes referred to as "rate" charts) deal with event counts when the area of opportunity is not constant during each period. The steps to follow for constructing a u-chart are the same as a c-chart, except that the control limits are computed for each individual quarter because the number of standard units varies.

P-chart

P-charts (sometimes referred to as "proportion" charts) are used to show the fraction nonconforming of a nonstandard sample size over a constant area of opportunity (e.g., each period of interest). The steps to follow for constructing a P-chart are the same as a c-chart, except that the control limits are computed for each time period because the sample size varies.

NP-chart

Like p-charts, np-charts are used to analyze nonconforming items over a constant area of opportunity; however, the np-chart focuses on the number of nonconforming items when the sample size is constant. The steps to follow for constructing an np-chart are the same as for a p-chart.

Use of Control Charts

Control charts serve to direct management attention toward special causes of variation in a system when they appear. Limit lines drawn on the charts provide guides for evaluation of performance. These lines (called control lines) indicate the dispersion of data on a statistical basis and indicate if an abnormal situation (e.g., the process is not in control or special causes are adversely influencing a process in control) has occurred.

In evaluating control charts, managers should look for the following indications:

- Outliers - Data that fall outside the control lines.
- Runs - Series of data points over or below the central line. A "run" of 7 consecutive points or 10 out of 11 points indicates an abnormality. Other approaches exist for identifying runs, such as detecting two of the last three data points beyond two standard deviations (2-sigma) and the more general CUSUM (cumulative sum discussed in Section 3.2.7) procedures, which involve adding up standardized deviations from the calculated mean to detect abnormalities (such as runs or trends) sooner.
- Trends - Continual rise or fall of data points. If seven data points rise or fall continuously, an abnormality is considered to exist.
- Periodicity - Data show the same pattern of change over time. Also known as a cyclical pattern.

In summary, the two main uses for control charts are: (1) to monitor whether the system is stable and under control (to warn of changes), and (2) to substantiate results from changes introduced into the system (to confirm results).

Treatment of "Outliers"

In constructing control charts, individual or groups of data points may appear near or beyond the calculated control limit lines. Since these data appear to indicate that a system is or may not be in control (e.g., stable), additional evaluation may be needed to ascertain if the data in question are the result of common cause or special cause variation. If the data are clearly influenced by a one-time aberration (e.g., special cause), there could be a basis for excluding the number or estimating what the actual value should have been for the purpose of determining actual system control limits.

Treatment of "Rare" Events

For trending PI data using c- and u-charts, the average used to calculate control limits should be equal to or greater than five. Where the limited nature of the data does not support the use of control charts, the use of more sensitive trend tests may provide a better indication of actual trends. An example would be multinomial likelihood ratio tests that involve comparing the likelihood of postulated rates of data change (e.g., constant, increasing, or decreasing) assuming the data are generated by a multinomial distribution.

Scaling of Control Charts

The following general criteria should be applied to the depiction of trend data on control charts: (1) the scale should be set so that the chart can be quickly understood, and (2) the data together with the limit lines should span at least half of the vertical axis.

Histograms

A histogram is a bar chart. It is designed to show:

- a distribution or spread of data
- the numbers of times various measurement values occur
- groups of values so patterns of variation are easily identifiable
- the average as well as variability of a data set

Histograms are most often used to record frequency of events associated with measurements of time or cost. Histograms may be used when the characteristics of one or more sets of data need to be summarized, when checking for possible variations in incoming data, and when absolute values reveal less information than trends and patterns would. The viewer can quickly and easily see the shape of the distribution of a process, which may lead to further analysis of correlation.
Listed below are the elements of a histogram and an explanation of what each element displays:

- Horizontal axis: lists measurement values.
- Vertical axis: shows frequency or amount of values.
- Width of each bar: represents an arbitrary range of values.
- Height of each bar: represents the number of times the values within specified range are observed.
- Pattern created by the bar heights: displays a graphic distribution.

How to Construct a Histogram

To construct a histogram, you should collect as many measurable data points as possible using a frequency table. Spreadsheet software programs (e.g., Excel or Access) are the best way to collect and store frequency tables. As a general statistical rule, at least 100 measurement values are required for an accurate distribution picture and at least 30 data points are required for reliable regression analysis.

1. Determine the number of bars or intervals.
The number of intervals, bars, or columns is based on the total number of measurement values collected. Example:

Number of Measurements	Number of Bars
Under 50	5-7
50-100	6-10
100-249	7-12
Over 249	10-20

2. Determine the range of the bars.
Find the overall range of the data by subtracting the smallest value from the largest value. Then divide the overall range by the number of bars to determine the range of each bar. Round your answers up to a convenient value.

3. Determine the starting point of each interval and the bar limits.
Start with the smallest data point as the starting point of the first interval. Add the interval width that was determined to be the range of each bar. The sum is the starting point for the next interval. These are interval labels for the horizontal axis. It is customary to extend the scale one interval above and below range.

4. Construct a histogram worksheet or document the spreadsheet.
Identify the purpose, date, names of data collector and data source, the sample size, time period, and unit of measure. Record the limits for each bar, the tally of measurement values it represents, and the total frequencies of those values.

5. Construct the histogram.
Label the axes. List the values for the bar limits from left to right on the horizontal axis. Label the vertical axis with a scale large enough to accommodate the frequency of the tallest bar. Each data point can appear in only one interval. To make sure that no measurement values fall on either edge of a bar, add a logical decimal value to each limit.

Draw each bar to the height that corresponds to the frequency of the values it represents. A bar or column is centered around the midpoint of its interval.

6. Interpret the completed histogram.
Look for one of the patterns described below and consider the recommended actions to investigate the causes of non-normal distributions. To make it easier to compare the distribution to a standard or an average value, draw a dashed line for reference on the diagram. Figure 2.3 provides examples of these different distribution types.

- **Normal:** Not caused by any identifiable variable. Desirable distribution, no action required.
- **Saw-toothed:** Range of values for each bar is not the same or certain values were excluded from the range. Review the bar widths on the horizontal axis and/or check the source of the data and the way the data were gathered.
- **Bi-modal:** Variation maybe the result of cyclical factors or two sources of data. If two sources of data are combined, try to separate them. If cycles are expected, no action is required.
- **Skewed:** Sometimes the pattern is expected, especially with measurement of time.

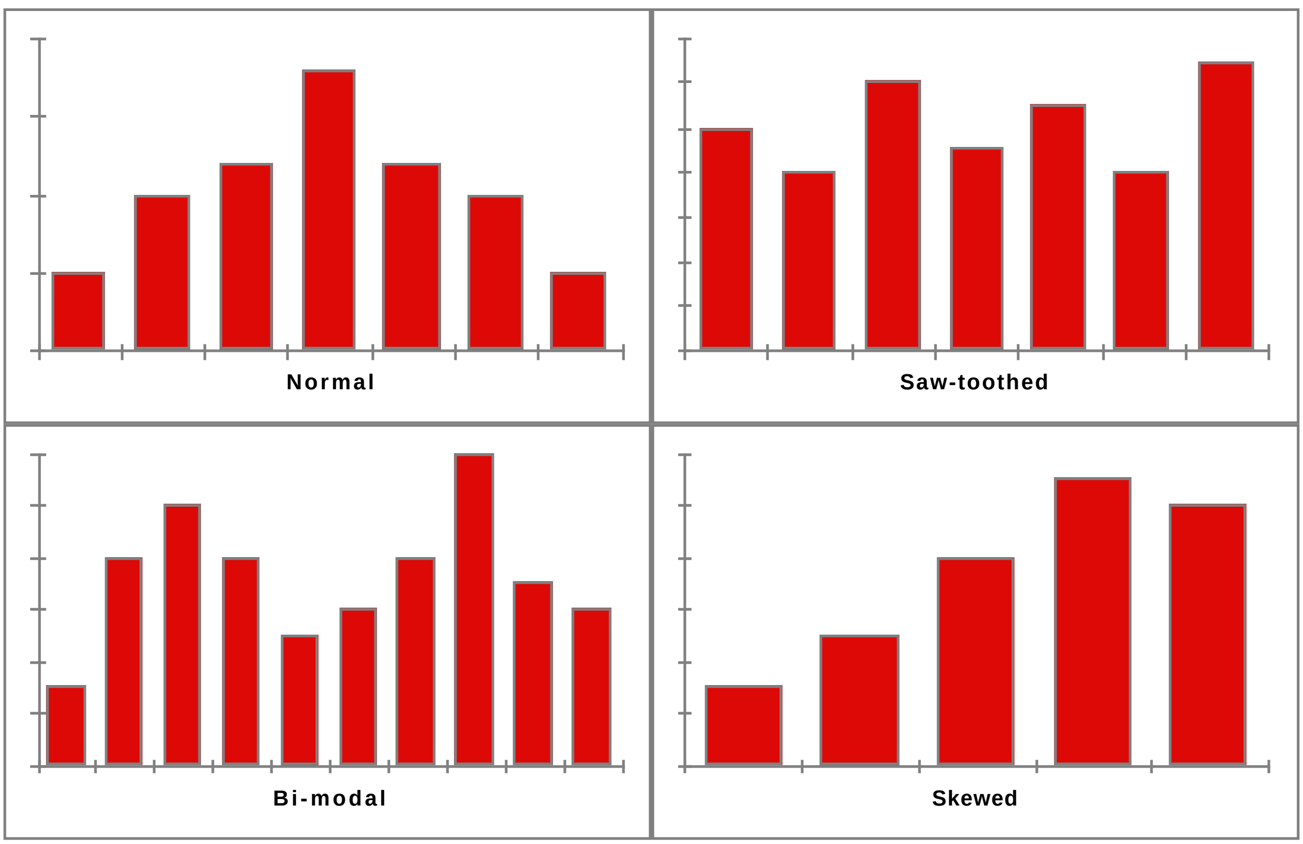

Figure 2.3
Types of Distributions

How to Display a Histogram - Software

Excel and Access are common spreadsheet databases used for data collection and storage. They will automatically graph frequency data into histogram format as desired. Histograms are most effective for visual analysis of population data where correlations may be further investigated. When graphing histograms, always ask if the picture is reasonable and logically correct; there is always the danger that software programs can make graphically pleasing displays from illogical input.

The Pareto Principle

The Pareto Principle derives its name from Vilfredo Federico Domaso Pareto, an Italian-Swiss socio-economist and trained, practicing engineer. As Chair of Economics in the Faculty of Law at Lausanne University in 1892 and forerunner in the field of mathematical approaches to socio-economics problems, Pareto conducted a study of the distribution of personal incomes of an entire economy. This led him to postulate that:

- Personal income will be distributed among the populace along the same lines in all countries.
- The pattern of income distribution cannot be easily changed.
- The number of incomes was more concentrated among the lower income groups.
- The majority of the wealth was in the hand of a few individuals.

Pareto postulated that, in an entire economic population, only a few individuals controlled the majority of wealth. This proved to be valid and become known as Pareto's Law, Pareto's Concept, or Pareto's Principle. Historically, the Pareto Principle has come to be more universally known as the 80/20 rule, i.e., an 80% improvement in quality or performance can reasonably be expected by eliminating 20% of the causes of unacceptable quality or performance.

Dr. Joseph M. Juran, Chairman Emeritus, Juran Institute, and world-renowned authority on quality management, was the first to apply this concept to the industrial environment. He noted that in many situations where a group of factors contribute to a common effect, only a vital few account for the bulk of the effect, and the useful many in the population account for the rest. Many problems associated with quality and performance adhere to this principle to identify and separate the vital few from the useful many.

The Pareto Concept

The simplicity of the Pareto concept makes it prone to be underestimated and overlooked as a key tool for quality improvement. Generally, individuals tend to think they know the important problem areas requiring attention; if we know, why do the problem areas exist? The most benefit derived from a Pareto analysis is to identify and define improvements for quality or performance improvement.

The idea is quite simple, but to gain a working knowledge of the Pareto Principle and its application, it is necessary to understand these basic elements:

- **Pareto Analysis** - creating a pictorial array of representative sample data that ranks the parts to the whole, with the objective to use the facts to find the highest concentration of quality improvement potential in the fewest number of projects or remedies to achieve the highest return for the investment.
- **Pareto Diagram** - the Category Contribution, the causes of whatever is being investigated, are listed and a percentage is assigned for each (Relative Frequency) to total 100%. A vertical bar chart is constructed, from left to right, in order of magnitude, using the percentages for each category.
- **Relative Frequency** = [(Category Contribution) / (Total of all Categories)] x 100 expressed in bar chart form.
- **Cumulative Frequency** = [(Relative Frequency of Category Contribution) + (Previous Cumulative Frequency)] expressed as a line graph with points of the line determined from the right edge of each bar or as a stacked bar chart.
- **Break Point** - the percentage point on the line graph for Cumulative Frequency at which there is a significant decrease in the slope of the plotted line.
- **Vital Few** - Category Contributions that appear to the left of the Break Point account for the bulk of the effect or those that account for the first 60 percent, or so, of the total.
- **Trivial Many** - Category Contributions that appear to the right of the Break Point, which account for the least of the effect.

Pareto Diagram Analysis

Pareto analysis provides the mechanism to control and direct effort by fact, not by emotion. It helps to clearly establish top priorities and to identify both profitable and unprofitable targets. Pareto analysis is useful to:

- Prioritize problems, goals, and objectives
- Identify root causes
- Select and define key quality improvement programs
- Select key customer relations and service programs
- Select key employee relations improvement programs
- Select and define key performance improvement programs
- Address the Vital Few and the Trivial Many causes of nonconformance
- Maximize research and product development time

- Verify operating procedures and manufacturing processes
- Product or services sales and distribution
- Allocate physical, financial and human resources

Pareto analysis may be applicable in the presentation of Performance Indicators data through selection of representative process characteristics that truly determine or directly or indirectly influence or confirm the desired quality or performance result or outcome. Typical observations from Paretodiagram analyses might reveal:

- 80% of all warranty repairs of a product were attributed to 20% of its parts.
- 75% of quality defects result from 15% of operations within a process.
- 10% of the items inventoried represent 70% of the total cost of inventory.

Pareto diagram observations may show the following: (1) that the bars are roughly the same size; (2) that it takes more than half of the categories to determine 60-80 percent; or (3) if the most frequent problem is not the most important. STOP after the first problem is resolved and develop a more discrete set of nonconformance cause parameters to survey, analyze, and diagram.

Process Capability

Process Capability is a determination of whether an existing process is capable of attaining the specified (or desired) performance. Process Capability has a precise, limited definition in a manufacturing context. This determination is based upon observing the history of the process output data. Statistical Process Control is used to determine the expected bounds of the data. These bounds (which are the three standard deviation control limits) are compared to the manufacturing specification for the process. A more general utilization of this concept can be applicable to Department of Energy facilities and processes.

Statistical Control

In order to assess process capability, the process must first be in statistical control. The data that have been charted must be reviewed against their three standard deviation control limits. If no data points are outside of the control limits, and no discernible trends are detected (using the criteria given in the section on Control Charts beginning on Page 2-13), then the process is in control. The original work by Dr. Shewhart emphasized strongly that a process should not be declared in control unless the pattern of random variation has persisted for some time and for a sizable volume of output. He recommended taking at least 25 samples (data points) prior to declaring a process is in control. However, assessments using less data may be made. Using less data for the assessment takes some experience and can become more of an art than a science.

In some cases, a process with a single data point outside of the control limits may still be assessed as in control. To do this requires investigation of the cause(s) for the single data point being unusual. In short, if you can assign a reason for the value of the out-of-control point, and you can reasonably state that such an event will not reoccur, then you should disregard this point, treat it as an outlier, and not include it in the average or control limit calculations.

With the determination that the process is in control, you have also accepted the hypothesis that the process data will continue to behave as the past data have. It will continue to have the same average, and 99.7% of all future data points will fall between the upper and lower (three standard deviation) control limits. All variations that occur in the future data can be assumed to be due to random variation. This has important implications for management of the process, which will be explored later in this section.

Process Capability Analysis

Once the process is in control, the upper and lower control limits may be compared to the specification limits for the process. Generally, specification limits exist in manufacturing processes; for example, the diameter of the bolt shall be 5 cm plus or minus .01 cm. If the upper and lower control limits for bolt size were 5.01 and 4.98 cm, then we would fail the process capability determination (4.98 cm is outside the lower specification limit of 4.99 cm). If we improved our bolt manufacturing such that the new control limits were 4.993 and 5.007 cm, then we would have an acceptable process capability. That is, it would be highly unlikely (less than .3 percent) that we would manufacture a bolt that would fail the specification limits.

Note that even if our process has an acceptable process capability, we should still continue to practice continuous improvement and strive to minimize the variation in bolt sizes to be as close to 5 cm as is economically feasible. Reducing the variation in component sizes does tend to reduce several hidden costs (an undersize bolt paired with an oversize nut) when processes are highly variable. It may be economically worthwhile to consistently provide bolts that are much better than the specification.

If the control chart(s) are in statistical control, then calculate the process capability by comparing the natural tolerance (NT) of the process to the engineering tolerance (ET) of the specifications:

- NT = Upper Control Limit - Lower Control Limit
- ET = Upper Specification Limit - Lower Specification Limit.

If NT £ ET, the process is capable of meeting specifications. If NT > ET, then the process is not capable of meeting specifications.

At this point, if you are studying variables data and your process is in control and capable, you may want to investigate whether the process is in control with respect to the average. Depending on the data, X-bar and R-charts, or X-bar and s-charts must be graphed. Methods to describe this charting are described in detail in the Western Electric Company's *AT&T Statistical Quality Control Handbook*, 1984.

The same statistical rules listed in the section on Control Charts (beginning on Page 2-13) apply to determine if the charts are in control. If the charts are in control, then calculate a Capability Ratio (CR):

$$CR = (UCL - LCL) / (USL - LSL).$$

A good capability ratio should be less than one. Also, a Capability Index (C_{PK}) must be calculated.

$$C_{pk} = (USL - \text{X-bar})/3s \qquad \textbf{or} \qquad C_{pk} = (LSL - \text{X-bar})/3s$$

Select whichever calculation yields the smaller index. A good capability index should be greater than one.

Now, estimate the percent of product that will be produced out of specification by calculating a Z score.

$$Z_{high} = |(USL - \text{X-bar})/s| \qquad \textbf{or} \qquad Z_{low} = |(LSL - \text{X-bar})/s$$

If the absolute value of Z is >=3, then there are essentially zero defects. However, if the absolute value of Z is < 3, there are defects. A comparison of the Z score value on a Z table will provide an estimate of the percent of product that will be out of specification. Z tables can be found in many statistics textbooks, including *Statistical Quality Control*, 1989, by Grant and Leavenworth.

Use of Process Capability at DOE Facilities

Generally, the DOE facilities are not involved in producing bolts that must meet a specified limit. However, being aware of the process control limits is important for management of DOE facilities. A primary goal of Statistical Process Control and Performance Indicators is to communicate the capabilities of the process being analyzed. If the process is not in control, then efforts should be taken to understand why the process is out of control.

If there are a number of outlying data points (outside of the control limits, also known as outliers), the effort should be made to determine the cause(s) that drove the points out of control. These causes should then be used as a basis for management action to bring the process into control. A process that is forever fluctuating in an unknown manner is nearly impossible to manage. Bringing the process "in control" allows for the use of the control limits to predict future behavior of the process.

If there is a discernible trend, then there is an ongoing process change. If this trend is a result of a management action taken to improve the process and the trend is in the improving direction, then promote the trend. Eventually the effect of the change will stabilize, and you can compute new average and control limits once the process is again in control. The new average and control limits may be compared to the previous average and control limits to assess the impact of the management action. If the process data have a discernible trend, but there is no known action that caused it, then the cause(s) of the trend must be investigated.

If a major process change has just been implemented, then one would not expect the process to be in control. After these changes have been implemented, the process should eventually stabilize with a new average and new control limits. If you discover that you are continually making major process changes and the process data are becoming increasingly erratic, you may be experiencing process tampering as previously mentioned in this handbook.

Management Philosophy

Use of Statistical Process Control with Performance Indicator data provides important information for managers. Managers can use the process capability information in order to manage the processes they are responsible for. The control limits provide a reasonable guarantee of the expected extreme values of the process data. If these extreme values (and/or the average) are determined to be unacceptable, then management must embark on process changes in order to improve the outcome of the process.

Many management philosophies focus upon outcomes. There is justification in this, as it can be said that without the bottom line positive outcomes and results, a company will not stay in business. However, it must be realized that outcomes are the result of processes. In order to change existing outcomes for the better, the process that created the outcomes in question must be understood, and management must create changes to these processes.

Dr. Deming has stated:

- Management's job is prediction and there is no prediction without theory.
- There are no data on the future. Data from the past must be used to form a base for prediction.
- 94% of the changes required for improvement will require action by management.

All of these management philosophy statements point to the importance of managers understanding the processes that they control. In order to improve, the existing process capability must be known. Statistical Process Control and Process Capability provide the tools to:

- Measure current performance.
- Describe the state of statistical control.
- Attain statistical control.
- Determine if process changes are needed.
- Determine the effects of process changes once implemented.

Scatter Diagram

The scatter diagram is a useful plot for identifying a potential relationship between two variables. The data are collected in pairs on the two variables, say (x_i, y_i), for I=1,2 . . . n. The y_i is plotted against the corresponding x_i. The shape of the scatter diagram often indicates what type of relationship may be occurring between the two variables.

Scatter diagrams aid in the interpretation of correlation. The correlation coefficient, denoted by r, is a measure of linear association between two variables. The values of r range from -1 to +1, inclusively. A value of r close to zero signifies little, if any, linear association between the variables. Values of r close to either -1 or +1 indicates a high degree of association. Positive values of r indicate that as one variable increases, the other increases. Negative values of r indicate that as one variable increases, the other decreases. A value of +1 (-1) indicates that the data fall on a positive (negative) straight line.

The correlation coefficient is a measure of linear association only. Scatter diagrams will indicate curved relationships if they exist. In addition, the correlation coefficient will be badly distorted by outlying data. The scatter diagram can be used to locate outliers to check for their validity. Scatter diagrams and correlation coefficients are useful for identifying potential relationships. Designed experiments must be used to verify causality.

Several example scatter diagrams and their correlation coefficients are indicated below in Figure 2.4.

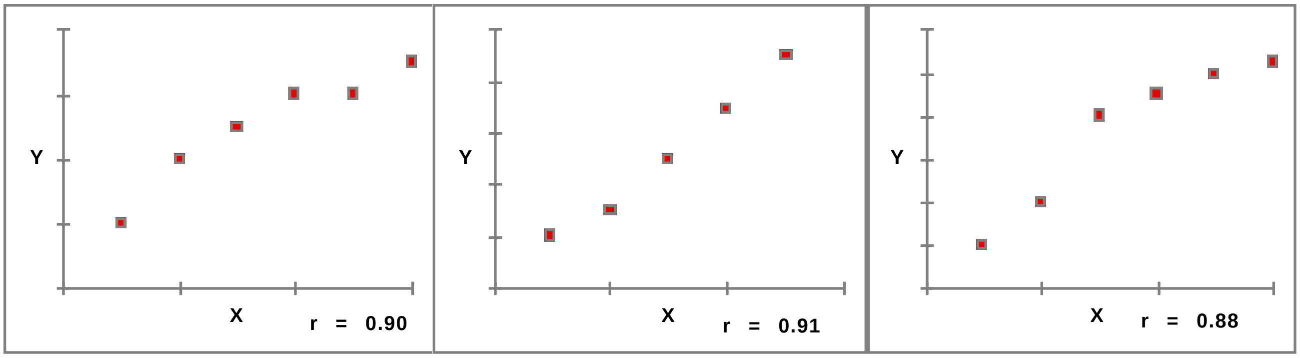

Figure 2.4
Scatter Plots and Correlation Coefficients

Cumulative Sum Trend Analysis Technique

Cumulative sum trend analysis can be applied to a performance measure to detect trends more quickly than standard control charting methods (i.e., Shewhart methods) are able to do. Cumulative sum trend applications are contained in most of the widely used PC-based statistics packages. Cumulative sum analysis is better at detecting small shifts (i.e., one standard deviation) of the process mean than standard control charting and provides an earlier indication of whether improvement efforts are succeeding or not, which is an important part of the evaluation of performance measures used in continuous improvement efforts.

A cumulative sum chart is a plot of the cumulative sequential differences between each data point and the process average over time. A positive slope of the graph indicates an average higher than the process average; a flat slope indicates an average the same as the process average; and a negative slope indicates an average less than the process average. Changes in the process averages are more easily seen plotted as a cumulative sum than in a standard control chart format.

Detection of a shift in the process average can be accomplished graphically with a horizontal V mask overlay on the plot of the cumulative sum data points. The user specifies the desired level of confidence and also the power of the method for detecting a change in the process average; for example, one standard deviation.

Determination of a trend shift is accomplished by centering the mask at a point of interest. The time at which the shift occurred is indicated where previous points cross one of the arms.

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